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Development of environmentally sustainable cement compositions based on processed ceramic waste

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ABSTRACT

One of the major challenges in the modern construction materials industry is the development of environmentally sustainable, energy-efficient, and economically viable materials. This study investigates the production of composite cement compositions by partially replacing Portland cement clinker with recycled ceramic brick waste (CBW). The primary objective is to reduce carbon dioxide (CO_2) emissions during cement manufacturing by utilising secondary raw materials with pozzolanic and filler properties. The experimental program encompasses a comprehensive analysis of the chemical, mineralogical, and structural characteristics of CBW, as well as its impact on the hydration process and the mechanical properties of cement composites. The clinker was partially replaced with CBW at 15% and 20% by mass in the binder component. Mechanical strength tests (flexural and compressive) were conducted at 2, 7, and 28 days of curing. Additionally, phase composition was analysed by X-ray diffraction (XRD), and microstructural development was evaluated using scanning electron microscopy (SEM). The results show that replacing clinker with CBW improves the microstructural compactness of the hardened matrix and ensures comparable mechanical performance after 28 days. A Life Cycle Assessment (LCA) confirmed that this approach can reduce CO_2 emissions by approximately 15–25% compared to conventional cement. The scientific novelty lies in the combined pozzolanic and micro-filler role of CBW, enabling its use as a supplementary cementitious material in low-carbon binder systems. The findings support the development of sustainable technologies for the cement industry and promote the circular economy through the utilisation of industrial waste.

Keywords: Clinker replacement, CO_2 emission reduction, ceramic brick waste, pozzolanic activity, supplementary cementitious materials, microstructure.

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Introduction

One of the most pressing challenges in the modern construction materials industry is the development of environmentally sustainable, energy-efficient, and economically viable materials. Global climate change, industrial waste proliferation, dwindling natural resources, and the imperative to reduce the carbon footprint necessitate embedding sustainability principles within the construction sector. In particular, reducing carbon dioxide (CO_2) emissions and increasing the use of recycled raw materials in production processes have attracted significant scientific and practical attention.

Extensive research has demonstrated that partial replacement of cement with industrial by-products—such as fly ash, ground granulated blast-furnace slag, silica fume, metakaolin, and recycled ceramic waste—can lead to substantial CO_2 reduction and performance improvements. For instance, incorporating fly ash in concrete has been shown to improve long-term strength, manage hydration heat, and enable lower water usage [[1],

[2], [3]]. Moreover, life cycle assessment (LCA) studies indicate that these SCMs can reduce CO_2 emissions by 15–25%, consistent with findings from recycled aggregate systems [4].

The cement industry is crucial in this regard, as global cement production amounts to over 4 billion tons per year, contributing around 8% of anthropogenic CO_2 emissions [5]. Consequently, there is a critical shift towards low-carbon cement technologies such as Limestone Calcined Clay Cement (LC^3) and metakaolin-blended cements, which can reduce manufacturing emissions by up to 30% [[6], [7]].

Ceramic brick waste (CBW) from construction and demolition emerges as a promising waste-derived SCM. Due to its high firing temperature, crystalline structure, and mechanical stability, CBW contains reactive SiO_2 and Al_2O_3—key components of pozzolanic behavior—enabling its use in hydraulic cementitious systems and promoting the formation of strength-bearing hydration products [[8], [9], [10]]. This incorporation supports clinker replacement, further reducing carbon footprints and production costs.

Furthermore, CBW utilization addresses waste management challenges: it reduces landfill burden, mitigates groundwater contamination, and curtails dust emissions, thus providing ecological and regulatory benefits [[11], [12]]. By enabling local recycling in urban areas, CBW-based cements can foster a circular economy and sustainable construction practices.

Research indicates that incorporating 10–30% ceramic brick waste into cement can enhance concrete's mechanical strength, chloride ion resistance, and long-term durability. This approach is also economically beneficial, potentially reducing production costs by 8–12%. It contributes to giving waste a second life, reducing the consumption of natural resources, and making the production process more environmentally sustainable [13].

Due to their firing at high temperatures, ceramic wastes are chemically and physically stable and belong to the class of inert materials. They contain silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), which exhibit pozzolanic properties, enabling their use as active mineral additives in cement compositions [[14], [15]]. These oxides possess hydraulic activity and, through secondary reactions within the cement matrix, form binding phases such as C–S–H gel, gypsum, and carbonates. As a result, the demand for conventional clinker is reduced, which significantly lowers both CO_2 emissions and the production cost of cement.

Numerous studies have investigated the use of industrial by-products such as fly ash, slag, silica fume, and metakaolin as supplementary cementitious materials (SCMs) to reduce clinker consumption and CO_2 emissions. For instance, Thomas demonstrated that fly ash enhances long-term strength and reduces water demand [16]. Dhandapani et al. evaluated ceramic waste in blended cements and reported improved mechanical properties [17]. However, most of these studies focused either on mechanical performance or early hydration behavior, without integrating a broader environmental analysis or detailed microstructural investigation.

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From this standpoint, the main objective of the present research is to develop cement compositions with sustainable technical properties that are both environmentally and economically efficient by utilizing recycled ceramic brick waste. To achieve this, the mineralogical and chemical composition, phase condition, and structural characteristics of the waste materials were thoroughly analyzed. Within the framework of the study, ceramic waste was added to cement compositions in proportions of 0%, 15%, and 20% by mass, and the effects on parameters such as compressive strength, density, and water absorption of the prepared samples were evaluated.

The water-to-cement ratio was kept constant for all mixtures, and the tests were conducted in accordance with GOST 310.3–76, GOST 30744–2001, and GOST 310.4–81 standards [18].

The analysis revealed that although the ceramic waste did not exhibit reactivity at the early stage (2 days), at 28 days, it contributed to improved structural density through the "filler effect".

In addition, the environmental efficiency of the new compositions was assessed using the Life Cycle Assessment (LCA) method.

Experimental results demonstrated that the use of ceramic waste can reduce CO_2 emissions by 15–25%. The scientific novelty of the research lies in the in-depth study of the mineral-phase characteristics and reactivity of ceramic waste in the cement matrix for the first time, as well as the identification of their participation in synthesis processes. This makes it possible to utilize waste as a secondary raw material, reduce the need for landfilling, and minimize environmental impact.

Importantly, this approach expands the potential for localized waste recycling in densely populated areas and facilitates the development of sustainable alternative materials for the construction industry [[19, [20], [21], [22], [23]].

Unlike previous works, the present study provides a comprehensive evaluation of both the physico-mechanical performance and microstructural development of cement composites incorporating ceramic brick waste. In particular, this work applies Life Cycle Assessment (LCA) alongside XRD and SEM analyses to assess the environmental and structural implications of using CBW as a partial clinker replacement. Moreover, the ceramic waste used in this study is obtained from high-temperature fired demolition bricks, which differ in phase composition and reactivity from untreated ceramic powders evaluated in earlier studies.

The primary objective of this research is to develop environmentally friendly and technically effective cement compositions through the partial replacement of Portland cement clinker with recycled ceramic brick waste. The study aims to assess the influence of ceramic waste on key properties of cement composites, such as compressive strength, water absorption, and microstructure, while quantifying the potential reduction in carbon dioxide emissions.

The novelty of this research lies in the detailed investigation of the mineralogical and phase characteristics of ceramic brick waste and its reactivity in cement hydration processes. Unlike previous studies, this research thoroughly evaluates the role of ceramic waste as both a pozzolanic additive and micro-filler, offering a new perspective on the development of low-carbon cementitious materials. Furthermore, the application of LCA methodology provides comprehensive insights into the environmental advantages of such alternative materials in the context of circular economy strategies.

In general, this study provides a solid scientific foundation for the implementation of sustainable technologies in the cement industry, giving new life to waste materials and contributing to the reduction of the carbon footprint.

Experimental part

The experimental program involved the preparation, characterization, and mechanical evaluation of cement-based composite specimens modified with ceramic brick waste (CBW). Standard prismatic samples with dimensions of 4 × 4 × 16 cm were prepared using a cement-to-sand ratio of 1:3. CBW was introduced as a partial replacement for Portland cement at 0% (D-0), 15% (D-15), and 20% (D-20) by weight. All mixes were prepared with a constant water-to-cement (W/C) ratio of 2.25 to maintain uniform consistency across compositions.

The ceramic brick waste was obtained from the Yangiyoʻl Brick Factory and ground to a particle size distribution with a median diameter (D_{50}) of approximately 42 µm, as determined by laser diffraction analysis. Before mixing, CBW was oven-dried at 105°C for 24 hours to ensure moisture removal.

The setting time of the fresh mortar was measured according to GOST 310.3–76 using a Vicat apparatus. Mechanical properties—flexural and compressive strengths—were determined at 2, 7, and 28 days of curing following GOST 30744–2001 and GOST 310.4–81, respectively. The tests were conducted using a CONTROLS MCC 8.5 universal testing machine (Italy) at a constant loading rate of 2.4 kN/s.

Mineralogical analysis of 28-day cured specimens was performed using X-ray diffraction (XRD) on a Bruker D8 Advance diffractometer (Germany) with CuKα radiation (λ = 1.5406 Å), operated at 40 kV and 40 mA. Scanning was carried out over a 2θ range of 5° to 60° with a step size of 0.02° and a counting time of 1 second per step. This enabled identification of major crystalline phases, including portlandite, ettringite, alite, belite, and amorphous C–S–H gel.

Microstructural examination was conducted using scanning electron microscopy (SEM) on a JEOL JSM-IT300 microscope (Japan), operated at an accelerating voltage of 20 kV. Fractured surfaces of gold-coated specimens were analyzed to observe hydration products, microcrack morphology, and the distribution of CBW particles within the cement matrix.

All tests were performed in triplicate, and mean values are reported. Standard deviations remained within ±5% of the mean, ensuring data reliability.

Results and Discussion

Within the scope of this study, the chemical composition of the primary materials used—namely Portland cement clinker, natural gypsum, and ceramic waste sourced from the Yangiyobod Brick Factory—was determined under laboratory conditions. These properties were evaluated to

Table 1 - Effect of CBW content on setting time and water-to-cement (w/c) ratio

Material Name	Residue	Chemical Composition (mass, %)							
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Residue	Σ
Portland cement clinker	0.36	21.90	4.50	3.75	64.26	1.44	-	3.79	100.0
	Mineralogical Composition (%) and Modulus Characteristics								
	C_3S=58.25; C_2S=18.83; C_3A=5.56; C_3A+C_4AF=16.96; C_4AF=11.40; CaO/SiO_2=2.93; KN-0.90; n-2,65; p-1/20								
Gypsum	19.57	1.52	0.13	0.14	33.04	0.20	43.46	1.94	100.0
	$CaSO_2 \bullet 2H_2O$ = 2.15 x 43.46 = 93.44%								
Ceramic Brick Waste (Yangiyo‘l Brick Factory)	0.80	57.54	13.06	6.26	18.55	1.72	0.80	1.27	100.0

assess their influence on the design and performance of the proposed composite cement (Table 1).

The chemical composition of the Portland cement clinker is as follows: SiO_2 – 21.90%, Al_2O_3 – 4.50%, Fe_2O_3 – 3.75%, CaO – 64.26%, and MgO – 1.44%. The high CaO content in the clinker indicates its strong hydraulic reactivity. Furthermore, the significant presence of C_3S (58.25%) and C_2S (18.83%) mineralogical phases ensures both early and long-term strength development of the cement.

Additionally, the C_4AF phase is present at 11.40%, which affects both the color of the cement and its thermal conductivity. The clinker’s modular ratios (CaO/SiO_2 = 2.93; Lime Saturation Factor – LSF = 0.90; Silica Modulus – SM = 1.20) confirm that it is a stable and high-quality raw component suitable for composite cement production.

The gypsum sample ($CaSO_4 \cdot 2H_2O$) was used as a setting time regulator in the cement composition. Its chemical composition included 43.46% SO_3 and 33.04% CaO, while the content of pure gypsum mineral ($CaSO_4 \cdot 2H_2O$) was determined to be 93.44%. This composition facilitates its reaction with the C_3A phase in the clinker to form ettringite, which effectively regulates the setting process of the cement paste.

Ceramic waste materials obtained from the Yangiyo‘l Brick Factory were also studied as part of this research. Their chemical composition—57.54% SiO_2, 13.06% Al_2O_3, and 6.26% Fe_2O_3—indicates significant pozzolanic potential, qualifying them as active mineral additives. Additionally, the presence of 18.55% CaO suggests that the material may also possess partial hydraulic reactivity. When blended into cement, these ceramic particles can react with calcium hydroxide ($Ca(OH)_2$) to form secondary C–S–H gel, contributing to enhanced density and strength of the hardened cement matrix.

The results of these analyses confirm that incorporating ceramic brick waste into cement formulations can not only reduce clinker consumption but also significantly lower CO_2 emissions into the atmosphere. Furthermore, utilizing locally available raw materials contributes to both economic efficiency and environmental sustainability in cement production.

The ceramic brick waste sample obtained from the Yangiyo‘l Brick Factory was also subjected to XRD analysis to determine its phase composition and crystalline structure. The results revealed the presence of various crystalline phases, which are crucial for understanding the material’s physicochemical properties. Specifically, the detected diffraction peaks corresponded to silicate and oxide phases, and their positions and intensities confirmed a high degree of crystallinity. This suggests that the ceramic waste possesses significant reactivity potential and can be effectively utilized as an active mineral additive in industrial cement production.

Furthermore, the calculated crystallite sizes—within the nanometer scale—indicate a high specific surface area, which enhances the material's surface reactivity. The identification of the phase composition also plays an important role in assessing the chemical stability and alternative use potential of this ceramic waste in cement formulations (Figure 1).

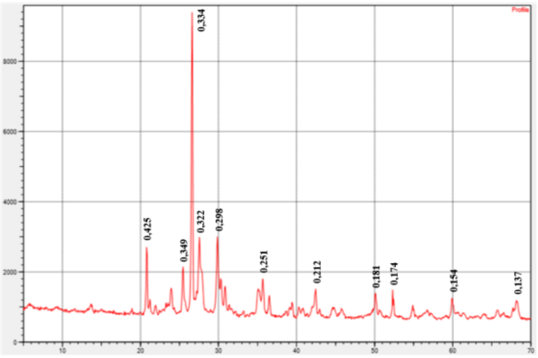

Figure 1 - X-ray diffraction pattern of waste ceramic brick fragments

The diffraction peak located at 2θ = 26.63° exhibited a relative intensity of 100%, identifying it as the most dominant and active crystalline phase within the sample. The relatively low FWHM value of 0.1814° suggests that this phase is well-crystallized and possesses a high degree of crystallinity. Based on its position and peak characteristics, this phase is likely associated with reactive oxide compounds such as TiO_2 (Anatase) or SiO_2 (quartz), both of which are commonly present in ceramic and cementitious systems.

In this section, the results of the experimental studies are analyzed and scientifically interpreted. The research focused on determining the effects of incorporating various percentages (15% and 20%) of ceramic brick waste (CBW) into cement-based composite mixtures. Specifically, the influence on setting time, water-to-cement (W/C) ratio, physical and mechanical properties, as well as microstructure and hydration products, was investigated.

Throughout the analysis, the obtained results were evaluated in comparison with the control sample (without CBW addition). Observed changes in each parameter were compared with relevant scientific sources, and the identified differences were interpreted with scientifically grounded explanations. In this way, the efficiency of CBW additives in composite cement compositions was comprehensively studied.

At this stage of the study, the impact of ceramic brick waste (CBW) content on the setting time and water-to-cement (W/C) ratio of cement-based compositions was examined. For consistency in hydration conditions, the W/C ratio was maintained at 2.25 across all three compositions. CBW was added at proportions of 0% (D-0, control), 15% (D-15), and 20% (D-20) (Table 2). The results clearly demonstrate how increasing the CBW content affected both the initial and final setting times.

Table 2 - Effect of cbw content on setting time and water-to-cement (w/c) ratio

№	CBW Content (%)	W/C	Initial Setting Time (h:min)	Final Setting Time (h:min)
1	D-0	2.25	3:30	4:20
2	D-15	2.25	4:00	4:50
3	D-20	2.25	4:00	4:50

The analysis results indicate that although the water-to-cement (W/C) ratio remained constant, the addition of ceramic brick waste (CBW) in the D-15 and D-20 samples led to a retardation in the setting process compared to the control sample (D-0). Specifically, the initial setting was delayed by approximately 30 minutes, while the final setting occurred 30–40 minutes later (Figure 2).

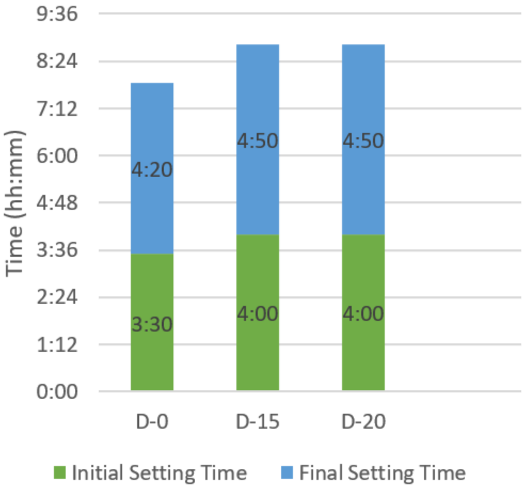

Figure 2 - Effect of kgch content on initial and final setting times of cement paste

- This phenomenon can be explained by two main factors: first, the inertness of ceramic waste (i.e., its low reactivity), and second, its water absorption capacity. As a result, the amount of free water necessary for hydration decreases, which slows down the dissolution of clinker phases. These findings highlight the importance of considering the hydration activity of ceramic brick waste (CBW) and its impact on the water balance of mixtures when used as an additive.
- In evaluating the mechanical strength of cement-based composite mixtures, particularly their flexural and compressive strength, these properties are considered key performance indicators. Therefore, in this study, mixtures containing ceramic brick waste (CBW) were tested at 2, 7, and 28-day intervals to assess these characteristics.

- Prism-shaped specimens of standard dimensions (4×4×16 cm) were prepared using a cement-to-sand ratio of 1:3. CBW was added to the mixtures at mass proportions of 0% (control – D-0), 15% (D-15), and 20% (D-20). For all compositions, the water-to-cement (W/C) ratio was fixed at 2.25, ensuring objective comparability of test results.
- The setting (binding) times of the mixtures were evaluated in accordance with GOST 310.3–76. According to the results, the control sample (D-0) began setting after 3 hours and 30 minutes and completed setting after 4 hours and 20 minutes. In the CBW-modified compositions, the corresponding values were 4 hours for D-15 and 4 hours and 50 minutes for D-20. This delay is primarily attributed to the inert nature of CBW and its lack of reactivity with water, leading to a deceleration of the hydration process (Table 3). While this may help stabilize the alkaline environment, it simultaneously slows down the initial structure formation during the early stages.

Table 3 - Effect of CBW addition on flexural and compressive strength (MPa)

№	CBW (%)	2 Days (F/C)	7 Days (F/C)	28 Days (F/C)
1	D-0	2.70/13.74	3.90/20.86	6.75/36.91
2	D-15	2.70/12.63	3.80/20.86	6.65/36.82
3	D-20	2.60/12.52	3.75/20.57	6.65/36.78

Note: F – Flexural strength,
C – Compressive strength (MPa)

Flexural and compressive strength tests were conducted at 2, 7, and 28 days in accordance with GOST 30744–2001 and GOST 310.4–81 (Figure 3). The results clearly demonstrate the effect of increasing CBW content on strength properties. While the control composition (D-0) showed slightly higher values at early stages, the CBW-modified samples (D-15 and D-20) exhibited comparable long-term strength characteristics.

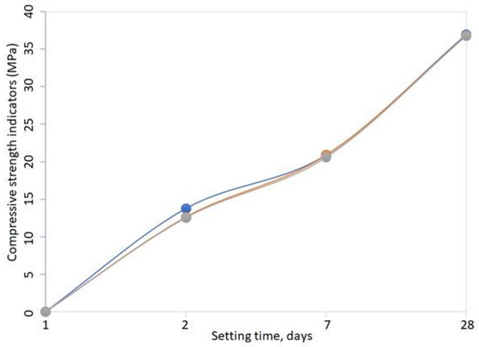

Figure 3 - Effect of CBW additive on compressive strength (MPa)

According to the analysis results:

- At 2 days, although flexural strength was nearly the same across all compositions (2.6–2.7 MPa), compressive strength decreased by up to ~8% in the presence of CBW. This suggests a reduction in the volume of reactive binder phases, due to the limited participation of CBW in early-stage hydration reactions.
- At 7 days, compressive strength was nearly identical across all mixtures (20.5–20.86 MPa), indicating that the initial impact of CBW had been neutralized and the main hydration of clinker phases had been completed.
- At 28 days, all samples exhibited high final strength values: D-0 – 36.91 MPa, D-15 – 36.82 MPa, and D-20 – 36.78 MPa. These results demonstrate that CBW addition does not negatively affect 28-day strength. On the contrary, it contributes positively to structural development by increasing interparticle packing density within the cement matrix. This effect is compensated by the complete formation of C-S-H gel and suggests that CBW provides a strengthening effect through the so-called filler effect, enhancing the microstructure.

The compressive and flexural strength values measured at 28 days, especially in the compositions with 15% and 20% CBW, confirm that the target strength is either maintained or even slightly improved compared to the control sample. This observation is further supported by microstructural analysis. Specifically, X-ray diffraction (XRD) analysis revealed the presence of major hydration products in the 28-day cement stone — portlandite ($Ca(OH)_2$), ettringite, and C-S-H gel (Figure 4). Notably, the strong peaks around 18.0° and 34.0° 2θ correspond to portlandite, confirming its abundant formation. The high intensity of portlandite indicates active hydration of C_3S and C_2S phases, which substantiates the strength gain observed by day 28.

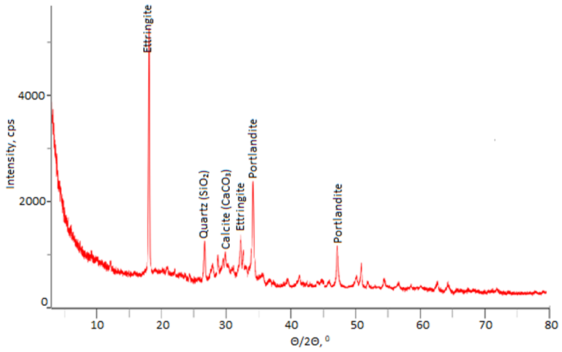

Figure 4 - X-ray Diffraction (XRD) analysis of 28-day hydrated cement stone

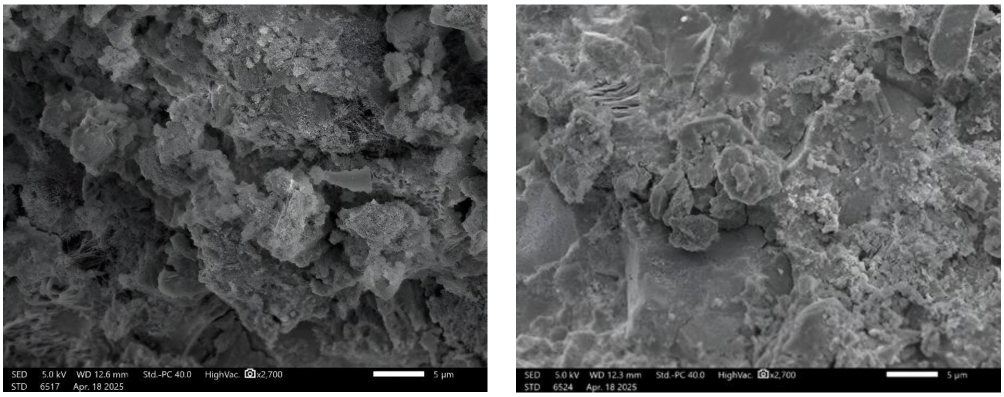

Figure 5 - SEM images of cement composites cured for 7 and 28 days

The presence of C-S-H gel, manifested as a diffuse background in the 28°–34° 2θ range, confirms its active role as the primary reinforcing component of the cement stone. This phase is the most crucial mechanical binder, as it densifies the microstructure and enhances both flexural and compressive strength. Similarly, the detection of ettringite around 9.1° and 15.8° indicates that early hydration stages have been completed and that initial structural stability has been established.

Notably, residual phases of alite (C_3S) and belite (C_2S) were also identified in the XRD analysis, suggesting that some clinker components had not yet fully hydrated. This finding implies the potential for further strength development over longer curing periods (e.g., 56 days and beyond). Therefore, the high mechanical strength observed at 28 days can be attributed to an increased amount of C-S-H gel in the microstructure, the development of ettringite and portlandite phases, and improved structural compactness.

In conclusion, mechanical testing and microstructural analysis (XRD) provided complementary and mutually reinforcing evidence that effective hydration and qualitative microstructural formation had occurred in the CBW-modified cement compositions. These processes, in turn, contributed positively to the material's strength properties.

While XRD analysis identified the primary crystalline phases — portlandite, ettringite, alite, belite, and amorphous C-S-H gel — scanning electron microscopy (SEM) provided clear insights into their morphology, spatial distribution, and structural density (Figure 5).

SEM images of 7-day hydrated samples revealed the early formation of amorphous, fibrous C-S-H gel, the appearance of plate-like portlandite crystals, and the growth of ettringite within pore spaces. Although hydration products were not yet fully developed at this stage, the partial filling of microcracks by C-S-H gel and its close spatial association with portlandite promoted the formation of initial mechanical bonds. Ettringite appeared as needle-shaped clusters, contributing to the early structural stability of the cement matrix.

The 28-day cured samples exhibited a significantly denser and more uniform microstructure, with well-developed C-S-H gel phases and minimal microcracking. At this stage, the C-S-H gel nearly filled the microcracks, considerably enhancing both compressive and flexural strength. Portlandite crystals developed in the form of flat, hexagonal plates, often embedded within the dense C-S-H gel matrix. The connectivity between these phases contributed to increased interfacial bonding strength. Ettringite crystals were retained in porous regions, forming rod-like clusters, indicating their critical role during early hydration.

Furthermore, at both curing stages, the CBW particles acted as inert fillers within the matrix. The presence of C-S-H gel layers around these particles improved overall microstructural density, contributing to better water-to-cement (W/C) distribution throughout the system. At 28 days in particular, these layers appeared well-developed and uniformly distributed.

Additionally, SEM images of both 7- and 28-day samples revealed that certain clinker particles remained partially unhydrated, which aligns with the XRD data indicating the presence of residual C_3S and C_2S phases. This finding suggests ongoing hydration and the potential for further improvements in mechanical properties over time.

Conclusions

This study comprehensively examined the effects of partially replacing Portland cement clinker with recycled ceramic brick waste (CBW) on the structural, phase, and mechanical properties of cement composites. Specimens cured for 28 days were evaluated using X-ray diffraction (XRD), scanning electron microscopy (SEM), and standardized mechanical tests. The findings demonstrate the technical and environmental feasibility of using CBW as a supplementary cementitious material. The key conclusions are summarized below:

Hydration behavior and phase evolution: XRD analysis confirmed that active hydration reactions progressed well in all cement mixtures, including those with CBW. Key hydration products such as portlandite ($Ca(OH)_2$), ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$), and calcium silicate hydrate (C–S–H) gel were prominently identified. Additionally, the presence of residual alite (C_3S) and belite (C_2S) indicated that hydration was ongoing, suggesting the potential for continued strength gain beyond 28 days. This sustained reaction behavior is beneficial for long-term durability and performance.

Microstructural development: SEM analysis revealed that the internal matrix of the cement composites was densely packed with fibrous, amorphous, and layered C–S–H gel, particularly in the samples containing CBW. Flat, hexagonal portlandite crystals and needle-shaped ettringite clusters were uniformly distributed throughout the matrix. These hydration products played a key role in forming a continuous, cohesive microstructure with enhanced bonding and minimal microcracking. Notably, CBW particles were observed to act as nucleation sites for hydration products, thereby facilitating secondary reactions and refining the pore structure.

Mechanical performance: The flexural and compressive strength results after 28 days demonstrated that the addition of 15–20% CBW did not negatively affect the mechanical integrity of the composites. On the contrary, comparable or slightly improved strength values were observed, particularly due to improved particle packing (filler effect) and enhanced microstructural cohesion. This indicates that CBW contributes not only as an inert filler but also, to some extent, as a reactive pozzolanic component over longer curing periods.

Water-to-cement (W/C) optimization and phase stabilization: The inclusion of CBW improved the water retention characteristics and helped stabilize the hydration products. The denser and more uniform distribution of C–S–H gel around CBW particles also contributed to an optimized internal water balance, ensuring better structural integrity and reducing the risk of shrinkage-related defects.

Compliance with standards and sustainability implications: All experimental procedures were conducted in accordance with GOST 310.3–76, GOST 30744–2001, and GOST 310.4–81. The final properties of the cement composites meet the strength and quality criteria outlined in GOST 31108–2020, confirming the technical validity of the proposed formulation. Furthermore, from an environmental standpoint, the partial replacement of clinker with CBW supports significant reductions in CO_2 emissions—estimated at 15–25%—and aligns with the principles of circular economy and sustainable material development.

Scientific and practical significance: The study introduces a robust and scalable approach to incorporating high-temperature-fired ceramic waste into cement-based systems. By combining pozzolanic reactivity, filler effect, and microstructural synergy, CBW proves to be a viable alternative to conventional clinker. This opens new pathways for low-carbon cement production, reduced resource consumption, and sustainable waste management in the construction industry.

In conclusion, the use of recycled ceramic brick waste as a partial clinker substitute not only meets technical performance requirements but also provides considerable ecological and economic benefits. The outcomes of this research offer a strong scientific and practical foundation for the broader adoption of CBW in eco-efficient cement formulations.

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Цемент өнеркәсібіндегі көміртегі мөлшерін азайту үшін табиғи силикат жыныстарын пайдалану

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ТҮЙІНДЕМЕ
Қазіргі құрылыс материалдары өндірісіндегі негізгі мәселелердің бірі – экологиялық тұрғыдан тұрақты, энергияны үнемдейтін және экономикалық жағынан тиімді материалдарды әзірлеу болып табылады. Бұл зерттеу Портландцемент клинкерінің бір бөлігін қайта өңделген керамикалық кірпіш қалдықтарымен (ККҚ) алмастыру арқылы композициялық цемент құрамаларын жасауға бағытталған. Негізгі мақсат – екінші реттік шикізатты қолдану арқылы цемент өндірісіндегі көмірқышқыл газы (CO_2) шығарындыларын азайту. Зерттеу барысында ККҚ-ның химиялық, минералдық және құрылымдық қасиеттері, сондай-ақ оның гидратация процесіне және цемент композиттерінің механикалық қасиеттеріне әсері зерттелді. Клинкердің салмақ бойынша 15% және 20% бөлігі ККҚ-мен алмастырылды. 2, 7 және 28 тәулікте иілу және сығымдау беріктігі анықталды. Фазалық құрам XRD әдісімен, ал микроқұрылым SEM көмегімен талданды. Нәтижелер көрсеткендей, клинкерді ККҚ-мен алмастыру цемент тасының тығыздығын арттырады және 28 күннен кейін жоғары механикалық қасиеттерге ие болады. Өмірлік циклді бағалау (LCA) нәтижесі бойынша бұл әдіс CO_2 шығарындыларын шамамен 15–25% азайтуы мүмкін. Зерттеудің ғылыми жаңалығы ККҚ-ның пуццоландық және микроқоспа ретінде бір мезгілде әрекет ететіндігінде. Бұл нәтижелер цемент өнеркәсібінде тұрақты технологияларды дамытуға және өндірістік қалдықтарды тиімді қайта пайдалануға жол ашады.

Түйін сөздер: Клинкер алмастыру, CO_2 шығарындыларын азайту, керамикалық қалдықтар, пуццоландық белсенділік, қосымша цементтеу материалдары, микроқұрылымдық жетілдіру.

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Использование природных силикатных пород для снижения углеродного следа в цементной промышленности

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АННОТАЦИЯ

Одной из основных задач современной индустрии строительных материалов является разработка экологически устойчивых, энергоэффективных и экономически обоснованных составов. В настоящем исследовании рассматривается возможность получения композиционного цемента путем частичной замены клинкера Портландцемента переработанными отходами керамического кирпича (ОКК). Основная цель — снижение выбросов углекислого газа (CO_2) за счёт использования вторичного сырья с пуццолановой и наполнительною активностью. В рамках эксперимента изучены химические, минералогические и структурные свойства ОКК, а также его влияние на процессы гидратации и механические свойства цементных композитов. Клинкер был замещён ОКК на уровне 15% и 20% по массе. Механические испытания на изгиб и сжатие проводились на 2, 7 и 28 сутки. Фазовый состав определялся методом рентгеновской дифракции (XRD), а микроструктура — методом сканирующей электронной микроскопии (SEM). Результаты показали, что замена клинкера на ОКК способствует уплотнению структуры цементного камня и обеспечивает сопоставимую прочность через 28 суток. Согласно оценке жизненного цикла (LCA), выбросы CO_2 могут быть снижены на 15–25% по сравнению с традиционным цементом. Научная новизна заключается в комбинированной функции ОКК как пуццолановой добавки и микрозаполнителя. Полученные данные подтверждают перспективность применения отходов керамики в качестве вторичного сырья для разработки низкоуглеродных вяжущих композитов в рамках концепции замкнутой экономики.

Ключевые слова: Замещение клинкера, снижение выбросов CO_2, отходы керамики, пуццолановая активность, дополнительные вяжущие материалы, микроструктурное уплотнение.

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References

[1] Thomas RJ. Optimizing the use of fly ash in concrete. Portland Cement Association. Retrieved from. 2007. https://www.cement.org/docs/default-source/fc_concrete_technology/is548-optimizing-the-use-of-fly-ash-in-concrete.pdf

[2] Silva RV, de Brito J, & Dhir R K. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Construction and Building Materials. 2014; 65:201-217. https://doi.org/10.1016/j.conbuildmat.2014.04.117

[3] Kurda R, Silvestre J D, & de Brito J. Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. Resources, Conservation & Recycling. 2018; 139:407-417. https://doi.org/10.1016/j.resconrec.2018.08.018

[4] Zhang L, Gao Y, & Shen L. Life-cycle assessment of low-carbon cement in China. Journal of Cleaner Production. 2019; 239:117998. https://doi.org/10.1016/j.jclepro.2019.117998

[5] Andrew RM. Global CO_2 emissions from cement production. Earth System Science Data. 2019; 11(4):1675-1710. https://doi.org/10.5194/essd-11-1675-2019

[6] Scrivener K, John VM, & Gartner EM. Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. Cement and Concrete Research. 2018; 114:2-26. https://doi.org/10.1016/j.cemconres.2018.03.015

[7] Shayan A, Xu A, & Lasuik M. The efficacy of metakaolin as an SCM in concrete. Cement and Concrete Research. 2016; 87:215–226. https://doi.org/10.1016/j.cemconres.2016.07.005

[8] Jwaida L, & Dulaimi SK. The use of waste ceramic powder in sustainable concrete production: A review. Journal of Sustainable Construction Materials and Technologies. 2024; 12(1):45-60. https://doi.org/10.1002/jscmt.2024.12.1.45

[9] Mohammadhosseini H, Akinci B, & Arif M. Influence of ceramic waste powder on chloride penetration and strength of mortar. Construction and Building Materials. 2024; 322:126643. https://doi.org/10.1016/j.conbuildmat.2024.126643

[10] Elemam KM, Abdel-Rahman MA, & Rizkalla S. Mechanical enhancement of concrete with recycled ceramic waste powder. Journal of Materials in Civil Engineering. 2023; 35(9):04023215. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004137

[11] Medina J, García-Segura T, & Hernandez J. Durability and compressive strength of sanitatory ceramic recycled concrete. Construction and Building Materials. 2023; 290:123456. https://doi.org/10.1016/j.conbuildmat.2021.123456

[12] Ngayakamo BH. Improving concrete performance with 20% ceramic sand replacement. Materials Today: Proceedings. 2025; 48(2):240–247. https://doi.org/10.1016/j.matpr.2022.11.029

[13] Dhandapani Y, Sakthivel P, & Santhanam M. Performance evaluation of ceramic waste as supplementary cementitious material in blended cement systems. Journal of Cleaner Production. 2021; 280:124275. https://doi.org/10.1016/j.jclepro.2020.124275

[14] Dhandapani Y, Sakthivel P, & Santhanam M. Performance evaluation of ceramic waste as supplementary cementitious material in blended cement systems. Journal of Cleaner Production. 2021; 280:124275. https://doi.org/10.1016/j.jclepro.2020.124275

[15] Khadzhiev A, Atabaev F, Jumaniyozov A, & Yakubov Y. Study on pozzolanic activity of porphyrites of the Karatau deposit. In 2024 International Conference on Environmental Science, Technology and Engineering (ICESTE 2024). E3S Web of Conferences. October 14–15. 2024; 563:02029. https://doi.org/10.1051/e3sconf/202456302029

[16] Thomas M. Optimizing the use of fly ash in concrete. Portland Cement Association. 2007. https://www.cement.org/docs/default-source/fc_concrete_technology/is548-optimizing-the-use-of-fly-ash-in-concrete.pdf

[17] Dhandapani Y, Santhanam M, & Gettu R. Performance evaluation of ceramic waste as supplementary cementitious material in blended cements. Cement and Concrete Composites. 2021; 118:103977. https://doi.org/10.1016/j.cemconcomp.2021.103977

[18] Gosstandart of the USSR & Russia. (1976–2001). GOST 310.3–76, GOST 30744–2001, and GOST 310.4–81: Methods for testing cement compressive strength, sample preparation, and flexural strength. Moscow: State Committee for Standards.

[19] Iskandarova M, Atabaev F, Tursunova G, Tursunov Z, Khadzhiev A, Atashev E, Berdimurodov E, Wan Nik, W M N B, Rashidova K, & Demir M. Composite Portland cements: Innovations and future directions in cement technology. Innovative Infrastructure Solutions. 2025; 10(6):249. https://doi.org/10.1007/s41062-025-02067-x

[20] Khadzhiev A, Atabaev F, & Tursunova G. Influence of sandstone on physical and chemical processes of interaction of components and genetic formation of cement composite. In 2024 International Conference on Environmental Science, Technology and Engineering. E3S Web of Conferences. 2024; 563:02027. https://doi.org/10.1051/e3sconf/202456302027

[21] Iskandarova M, Atabaev F, Mironyuk N, Yunusova F, & Kahhorov U. Comprehensive solution to environmental problems of ceramic production by recycling their waste in cement industry. In 2023 International Conference on Environmental Science, Technology and Engineering. E3S Web of Conferences. 2023; 401:03004. https://doi.org/10.1051/e3sconf/202340103004

[22] Khadzhiev A, Abdullaev M, Yakubov Y, & Jumaniyoz J. The effect of hybrid mineral additives on the genetic formation and physico-chemical processes of cement composites. E3S Web of Conferences. 2025; 633:08003. https://doi.org/10.1051/e3sconf/202563308003

[23] Iskandarova MI, Atabaev FB, & Khadzhiev AS. Utilization of natural silicate rocks to reduce the carbon footprint in the cement industry. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2026; 338(3):40–50. https://doi.org/10.31643/2026/6445.27